23.1 Active Circuits for Ultra-high Efficiency Micropower Generators using Nickel-63 Radioisotope

Rajesh Duggirala, Hui Li, Amit Lal

Cornell University, Ithaca, NY

Pervasive sensor nodes deployed in remote and inaccessible locations need long lifetime power sources to prevent cost prohibitive periodic replacement. This requires the power source to convert energy from a high energy density fuel into electrical energy at high conversion efficiency. Radioisotope fuels offer orders of magnitude higher energy density [1] when compared to conventional electrochemical or hydrocarbon fuels, and high-efficiency radioisotope power sources with volumes exceeding $100cm^3$ have been deployed in space satellites for decades. These power generators convert the thermal energy of high energy alpha radiation into electrical power using thermoelectric materials. However, implementing a small-scale high-efficiency radioisotope powered generator based on safe but less energetic beta radiation has been an unsolved challenge. High efficiency generators require less amount of radioisotope, which is important for both the safety and cost considerations.

Previous work has reported on Radioisotope-powered Piezoelectric micropower Generators (RPG) using Nickel-63 and its applicability to self-powered optical [2] and acoustic sensor micro-systems [3]. Here, we demonstrate the integration of betavoltiacs with RPG operating in new *resonant* modes, attaining nuclear-electrical conversion efficiencies of up to 30%. For efficient conversion of the RPG generated low amplitude ac signals, also presented is a 20mV forward voltage drop ac-to-dc rectifier employing radioactively biased MOSFETs. This result is also applicable to piezoelectric vibration scavengers in general. This establishes a technology threshold from which even a benign radioactive material like Nickel-63 can be used for micro-power generation for several decades as the half-life for Nickel-63 is 100.2years. Nickel-63 is a β-source with electron energies of 17keV, corresponding to a maximum penetration depth of less than 10μm in solids, thus enabling easy shielding. Moreover, the source is resistant to flaking, thus reducing risk of contamination while handling.

The architecture of the modified RPG is illustrated in Fig. 23.1.1. The β-voltaic cell at the tip of the cantilever beam traps the charged particles emitted from the thin-film radioactive source which has an activity of $1.5mCi/cm^2$, corresponding to $150nW/cm^2$ thermal power output. By charge conservation, the radioactive film is left with equal and opposite charges. This leads to an electrostatic force between the cantilever and the radioactive source, bending the cantilever and converting the radiated kinetic energy to stored mechanical energy. The electrostatic force eventually leads to pull-down of the cantilever, resulting in discharge and vibration of the piezoelectric unimorph beam (Fig. 23.1.2 (a)). This combined operation allows us to utilize both the charge and kinetic energy of the emitted electrons. The electrical signal for the piezoelectric can be rectified using a full-wave converter and used to charge a storage capacitor. In addition to the pulsed power output from the RPG at the end of every reciprocation cycle, there is a continuous DC power output from the betavoltaic cell. This 10nW to 20nW output can be used to power low-power sensors and retain charge in memory elements, while the pulsed 30μW to 40μW power can be used for sensing, computation and communications operations. We have used commercial Si p-n diodes as betavoltaic converters, obtaining an open-circuit voltage V_{OC} = 160mV with a corresponding short-circuit current I_{sc} = 35nA, leading to a power output of 3nW at a conversion efficiency of 1.8%. The integration of betavoltaics results in both the charge and the kinetic energy of the emitted β-particles being tapped for electrical energy generation, leading to efficiencies higher than a basic RPG.

The efficiency of the RPG increases with increasing average voltage across the air-gap as more of the kinetic energy of the emitted beta particles is converted into stored electrostatic energy. The ideal solution is to maintain the voltage across the air gap close to a value corresponding to the average energy of the particles, and sustain unimorph oscillations about that gap. This is demonstrated using the RPG setup shown in Fig. 23.1.3 (a). The betavoltaic charge collector is separated from the cantilever and the RPG air-gap is excited using a plate electrically connected to the source. The spring constant of the unimorph k, damping in the system b, the current output of the source I_s, the capacitance and leakage resistance of the air-gap between the source and betavoltaic C_p and R_{lp}, the capacitance and leakage resistance of the air-gap between the RPG and plate C_g and R_{lg}, and the gap g are used in a Simulink model as shown in Fig. 23.1.3(b). Simulation and experimental results (Fig. 23.1.4) show that local instability at certain values of gaps leads to parametric resonance amplifying ambient vibrations, giving a continuous AC signal output (Fig. 23.1.2(b)) at a very high conversion efficiency of 23%. By biasing the cantilever at one of the resonance points, this high conversion efficiency can be sustained.

Both in the resonant and the full reciprocation operation, the output ac voltages can vary from $10mV_{pp}$ to $10V_{pp}$. Operation at low voltages requires the voltage drop of the rectification circuit to be low for high-efficiency conversion of the generated power to DC voltage. One major limitation of a simple full-wave rectifier is the voltage drop that equals twice the forward voltage of the diode or threshold voltage of the diode connected MOSFETs used. In order to overcome this, we have developed zero turn-on voltage diode connected MOSFETs by actively biasing the MOSFETs (Fig. 23.1.5) with radioisotope-generated small DC biases [4]. These actively biased MOSFETs are used in a modified bridge rectifier topology as shown in Fig. 23.1.6, where the input signal is used to turn the radiation biased MOSFETs on. Measurements using 0.5μm SOS transistors show a reduction of the voltage drop from 450mV to 20mV. Although one can also use zero-volt-threshold transistors, using special fabrication technologies, our topology can be used with MOSFETs fabricated using *any* SOI technology as all one needs to do is to apply a bias close to the threshold voltage. This rectifier topology will result in harvesting of signal power levels never possible before.

Acknowledgements:
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References:
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[2] Amit Lal, Rajesh Duggirala and Hui Li, "Pervasive Power: A Radioisotope-Powered Piezoelectric Generator," *IEEE Pervasive Computing*, vol. 4, no. 1, pp. 53-61, Feb., 2005.
[3] Rajesh Duggirala, Hui Li and Amit Lal, "An autonomous self-powered acoustic transmitter using radioactive thin-films," *IEEE UFFC '04,* Digest, vol. 2, pp. 1318-1321, Aug., 2004.
[4] Kan, Shyi-Herng, Lal, A., "Self-powered IC-compatible DC-bias for Electrostatic Resonators," Proceedings of the *IEEE MEMS '04* Digest, pp. 817-820, Jan., 2004.

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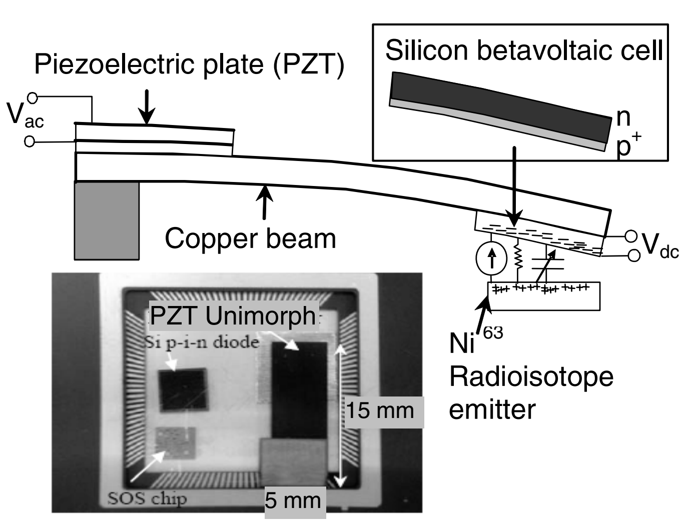


Figure 23.1.1: Schematic illustration of RPG, with the silicon betavoltaic cell magnified in the inset, and a photograph of a prototypical RPG assembly.

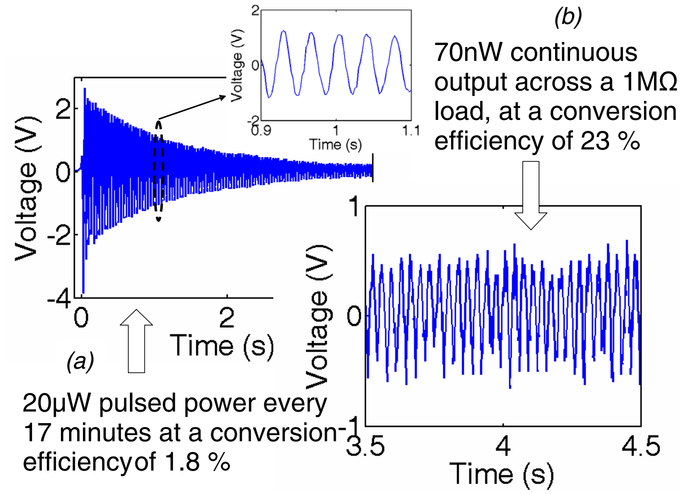


Figure 23.1.2: Measured output of PZT unimorph (a) at the end of a full-gap reciprocation cycle. (b) during the continuous (not just at the end of a reciprocation cycle) vibrations around certain points in the gap. In (b) the inset shows the cantilever vibrating at its natural frequency of 29Hz.

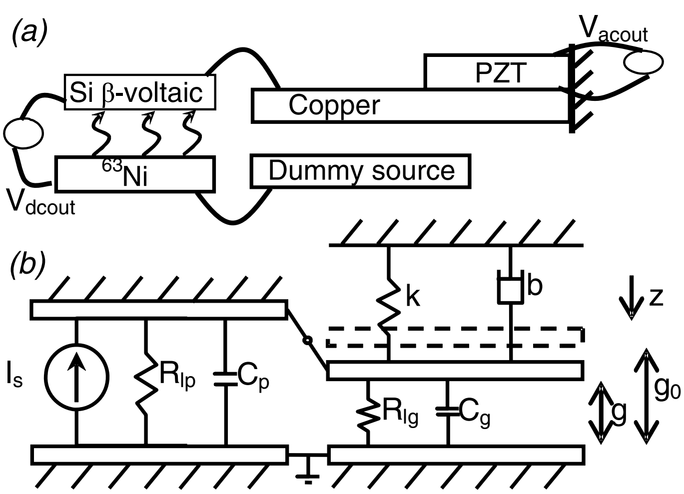


Figure 23.1.3: (a) Schematic illustration of a separate collector/unimorph RPG configuration and (b) its equivalent model used in Simulink.

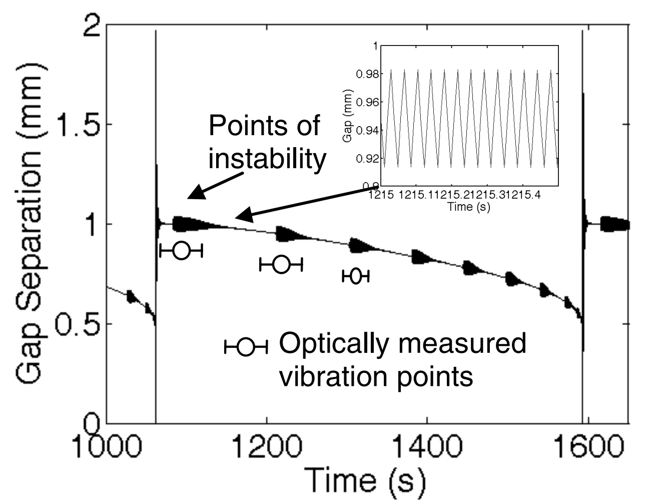


Figure 23.1.4: Plot from Simulink simulation and experimental observation proving continuous reciprocation in the RPG. Continuous reciprocation leads to ultra-high conversion efficiencies of 23%.

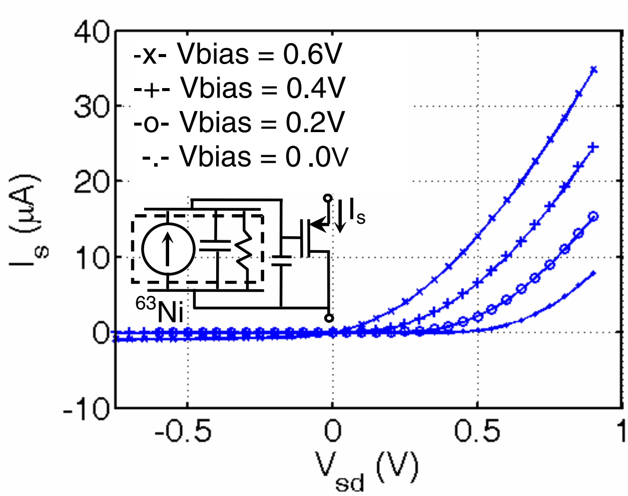


Figure 23.1.5: Measured Id-Vds curves P-MOSFET (fabricated in 0.5μm Peregrine Silicon on Sapphire technology) biased as shown in inset, with the electrical equivalent of the biasing circuitry shown.

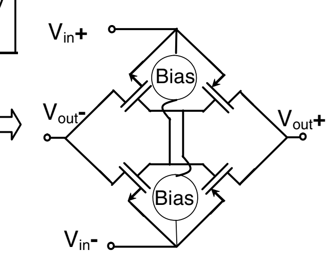
Topology			Voltage Drop
New topology		Vin < 300mV	20mV
		Vin > 300mV	< 10mV
Bridge rectifier with diodes			150mV
Bridge rectifier with diode connected MOSFETs without bias			450mV
Bridge rectifier with diode connected MOSFETs with Vgd = 0.5V			150mV

Figure 23.1.6: Table showing comparison of net rectifier voltage drop for different topologies. Inset: New bridge rectifier topology for reduced forward voltage drop using bias circuits in Fig. 23.1.5.

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